

Distribution of Surface Plastic Debris in the Eastern Pacific Ocean from an 11-Year Data Set

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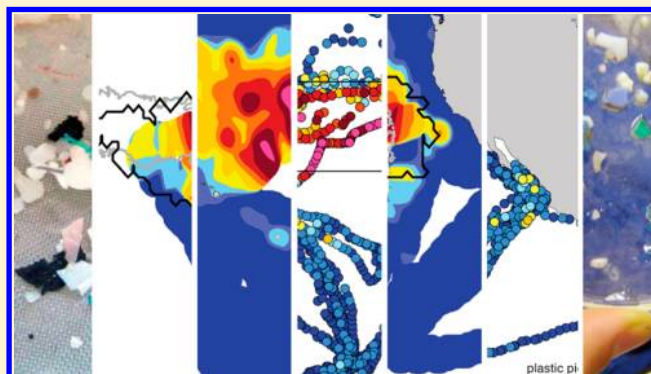
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S Supporting Information

ABSTRACT: We present an extensive survey of floating plastic debris in the eastern North and South Pacific Oceans from more than 2500 plankton net tows conducted between 2001 and 2012. From these data we defined an accumulation zone (25 to 41°N, 130 to 180°W) in the North Pacific subtropical gyre that closely corresponds to centers of accumulation resulting from the convergence of ocean surface currents predicted by several oceanographic numerical models. Maximum plastic concentrations from individual surface net tows exceeded 10^6 pieces km^{-2} , with concentrations decreasing with increasing distance from the predicted center of accumulation. Outside the North Pacific subtropical gyre the median plastic concentration was 0 pieces km^{-2} . We were unable to detect a robust temporal trend in the data set, perhaps because of confounded spatial and temporal variability. Large spatiotemporal variability in plastic concentration causes order of magnitude differences in summary statistics calculated over short time periods or in limited geographic areas. Utilizing all available plankton net data collected in the eastern Pacific Ocean (17.4°S to 61.0°N; 85.0 to 180.0°W) since 1999, we estimated a minimum of 21 290 t of floating microplastic.



INTRODUCTION

Scientists have studied floating plastic debris in the North Pacific Ocean for almost four decades, finding that marine plastics are widely distributed across the basin.^{1–3} Plastic debris is known to accumulate in subtropical convergence zones worldwide.^{4–6} Despite extensive public attention on the region of the eastern North Pacific subtropical gyre dubbed the “Great Pacific Garbage Patch,”⁷ only limited data exist to describe the spatial extent and temporal variability of floating plastic debris in the Pacific Ocean, especially in areas outside of the eastern subtropical gyre.

Known effects of marine plastic pollution include potential harm to sea turtles, seabirds, marine mammals, fish, and invertebrates from ingestion and entanglement.^{8–11} Plastic debris can transport non-native species^{12,13} including potential pathogens,¹⁴ and leach toxic contaminants into the ocean as well as sorb and transport other toxins already present in seawater.^{15–17} Recently, much of the research focus has shifted to microplastics (particles <5 mm in size¹⁸) because of their prevalence in the ocean and the potential ecological effects resulting from their wide accessibility to marine organisms.¹⁹

A recent comparison of surface plastic debris concentrations from 41 samples in the North Pacific subtropical gyre reported a 2 orders of magnitude increase in median concentration between 1972 to 1987 and 1999 to 2010.³ In contrast, a multidecadal survey in the North Atlantic subtropical gyre found no significant increase in surface plastic debris between 1986 and 2008;⁵ similarly, a study in the British Isles observed no increase in plastic abundance between the 1980s and 1990s.²⁰ Such conflicting trends raise important questions about the quantity, distribution, residence time, and fate of plastic debris in the open ocean, especially as global plastic production continues to accelerate.²¹

We present an 11-year time series (2001–2012) of surface plastic concentration in the eastern North and South Pacific Oceans (17.4°S to 57.5°N, 85.0 to 177.0°W), surveyed on annually repeated cruise tracks using consistent methods

Received: December 10, 2013

Revised: March 30, 2014

Accepted: April 7, 2014

Published: April 7, 2014

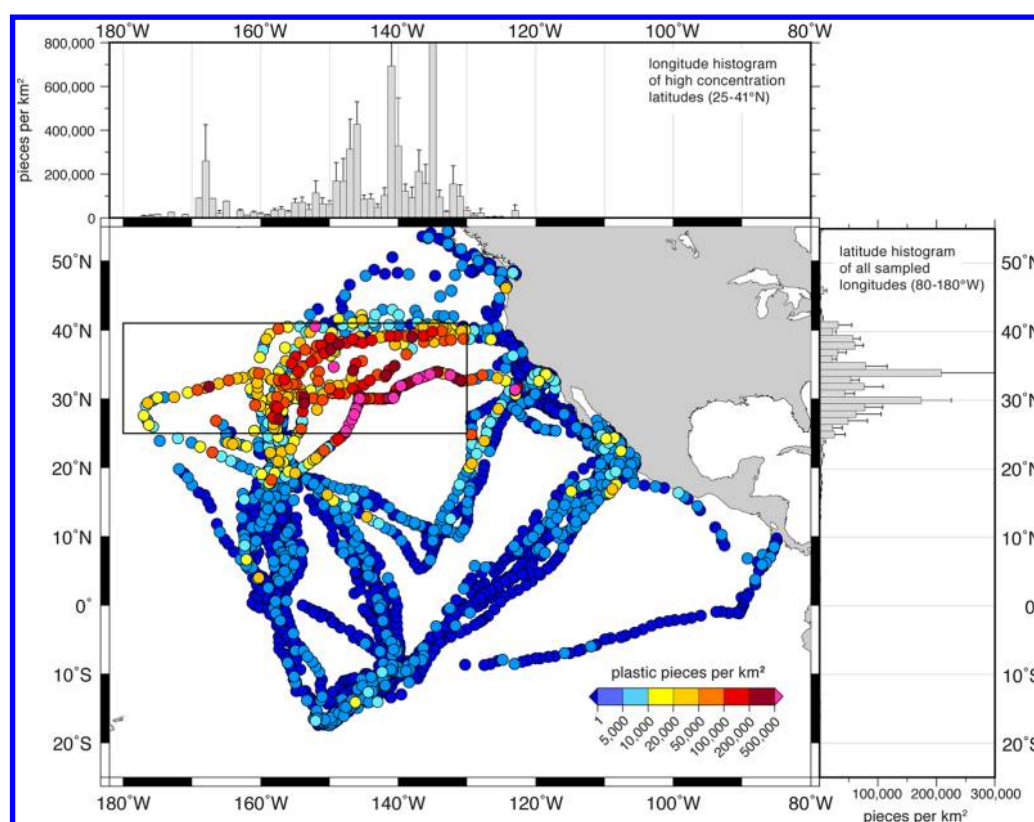


Figure 1. Distribution of plastic marine debris collected in 2529 SEA neuston net tows on annually repeated cruise tracks from 2001 to 2012 in the eastern North and South Pacific Oceans. Circles mark the location of each net tow and color indicates measured plastic concentration in pieces km^{-2} ; circles are layered from low to high concentration. The black box indicates the defined plastic accumulation zone (25 to 41°N, 130 to 180°W), containing 93% of total plastic pieces sampled. The histogram at right shows average plastic concentration with standard error (black lines) computed in 1° latitude bins across all longitudes; the histogram at top shows average plastic concentration with standard error computed in 1° longitude bins using only data between 25 and 41°N to accentuate the high concentrations observed in the subtropical gyre region.

throughout. Measured plastic concentrations from more than 2500 surface plankton net tows were used to determine spatial patterns in the distribution of floating plastic debris, to evaluate three oceanographic numerical models of variable design that predict accumulation patterns of surface debris, and to investigate temporal changes in the average amount of debris in the region of highest concentration. We combined this data set with previously published net data collected from 1972 to 2010, providing the most comprehensive plastic marine debris data set available for the eastern Pacific Ocean. We used this combined data set to evaluate the effects of irregular, nonrandom sampling on summary statistics that are frequently used to describe the extent of this pollution problem, and to estimate the minimum mass of floating microplastic measured in the entire net-surveyed region of the eastern Pacific Ocean since 1999.

EXPERIMENTAL SECTION

From October 2001 to December 2012 Sea Education Association (SEA) completed 96 research cruises during 11 annual circumnavigations of the eastern Pacific Ocean (Figure 1). Most cruises were carried out within the SEA Semester program, during which undergraduate students and faculty scientists conducted oceanographic research onboard SEA's sailing research vessel, SSV *Robert C. Seamans*. One notable exception was the *Plastics at SEA: North Pacific Expedition* (October to November 2012), the only SEA cruise designed to research near-surface plastic debris in the predicted region of

highest accumulation;²² for this reason, the *Plastics at SEA* cruise track departed from previous tracks.

In total, 2529 plankton net tows were conducted using a rectangular neuston net (335- μm mesh, 0.5 \times 1.0 m mouth) towed at the air-sea interface for 30 min at a nominal speed of 2 knots (3.7 km h^{-1}). Tow distance was determined three different ways: with a mechanical speed log deployed off the ship's stern that measures distance traveled through the water; as the calculated distance between GPS positions recorded at the start and end of the tow; and by the cumulative distance between GPS positions recorded every minute during the tow. Additionally, for the 97 net tows conducted during the *Plastics at SEA* cruise, the volume of water sampled was also measured using a flow meter suspended just below the net mouth. Because tow distance is used to compute the ocean surface area sampled by the net (tow distance \times 1-m net width) and ultimately plastic concentration, we conducted a comparative evaluation of each method (Supporting Information (SI)). Cumulative distance by GPS was the most reliable measure of water filtered by the neuston net. For consistency, tow distances for all net tows within the plastic accumulation zone (defined below) were postprocessed using the cumulative GPS method. Tow distance in the final data set ranged from 145 to 10 897 m, with 92% of tows between 1 and 3 km in length.

Following each tow, all plastic pieces visible to the naked eye (typically millimeters in size) were hand-picked out of the sample, enumerated, air-dried, and archived for future analysis. Industrial resin pellets, which are easily identifiable by visual

appearance, were counted separately from other particles. For three of the 2529 tows with extremely high concentrations, reported values were extrapolated from counts of a portion of each sample. Plastic concentration for each tow was computed as the total number of pieces collected (defined as pellets plus particles) divided by the tow area, reported in units of pieces km^{-2} . In addition, we compiled previously published net data collected from 1972 to 2010³ (SI, Table S1).

RESULTS AND DISCUSSION

Spatial Distribution of Floating Plastic Debris. Plastic debris was found in 42% of all surface net tows in the SEA data set, with industrial resin pellets constituting 2% of total pieces. The highest concentrations of total plastic pieces were observed between 25 and 41°N latitude (Figure 1). Within these latitudinal bounds, low plastic concentrations were observed along the west coast of the United States where low sea surface temperatures indicated the presence of the California Current, the current bounding the eastern edge of the subtropical gyre. In the western portion of the data set spanning the central subtropical gyre plastic concentrations were variable, exhibiting no clear decrease in concentration at any particular longitude. Based on the observed average concentrations in one-degree latitude and longitude bins (Figure 1), we visually defined a plastic accumulation zone (25 to 41°N, 130 to 180°W) within which 93% of all plastic pieces in the 11-year data set were collected.

Ninety-five percent (324/341) of the net tows conducted within the accumulation zone contained plastic pieces, in contrast to only 34% (734/2188) of tows outside the zone. The median plastic concentration of all tows within the accumulation zone was 3.309×10^4 pieces km^{-2} ; outside the zone the median value was 0 pieces km^{-2} (the median for nonzero tows outside the zone was 1.485×10^3 pieces km^{-2} ; additional statistics in SI, Table S2). Ninety-two percent (142/154) of all net tows with plastic concentrations greater than 50 000 pieces km^{-2} were conducted within the accumulation zone, including the largest sample collected in a single net tow (1.232×10^7 pieces km^{-2} at 33.57°N, 135.44°W). All plastic concentrations exceeding 10^6 pieces km^{-2} were measured during the *Plastics at SEA* cruise, which sampled the predicted area of highest concentration.

Physical Ocean Processes Influencing Surface Plastic Distribution. The spatial patterns observed in SEA's 11-year data set support the strong dependence of plastic distribution on upper ocean circulation. The plastic accumulation zone is associated with the large-scale subtropical convergence in surface currents created by wind-driven Ekman transport and geostrophic circulation, whereas areas of low plastic concentration correspond to regions of divergent surface flow associated with the North Pacific subpolar gyre and the equatorial current system.²³

Using numerical modeling techniques, three studies have independently predicted where floating debris would accumulate in the global ocean as a result of transport by ocean surface currents.^{22,24,25} Despite different modeling approaches (e.g., hydrodynamic vs data-based statistical model; steady-state vs time-evolving; uniform vs point-source inputs), all three models exhibit accumulation zones in the five subtropical gyres due to the presence of the large-scale convergence in surface currents. Furthermore, all models predict similar centers of accumulation in the eastern North Pacific (Figure 2), which strongly correspond to this study's area of highest observed plastic

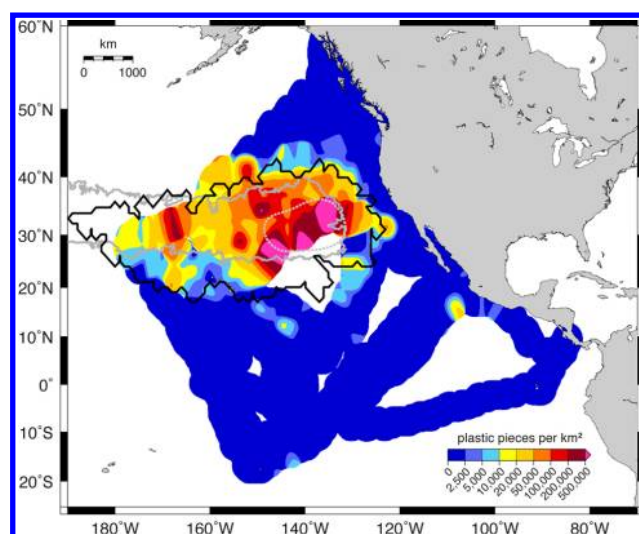


Figure 2. Average plastic concentration (color shading, units of pieces km^{-2}) computed by averaging data in Figure 1 in one-degree bins, regridding into 5 min bins, and smoothing with a 600 km full-width Gaussian filter. Overlaid lines represent the accumulation zones described in three numerical ocean models (dotted gray line;²² solid gray line;²⁴ black line²⁵), which were defined in each study using different criteria.

concentrations. While the location, strength, and extent of the subtropical convergence are determined by time-variable large-scale wind patterns, the spatial extent of the accumulation zone appears remarkably stable given the correspondence of our time-integrated data set to predictions by numerical models differing substantially in design.

The large-scale (1000 s km) plastic debris distribution pattern defining the accumulation zone is robust, but we note substantial variability in plastic concentrations at smaller spatial scales. Typical spacing between our surface net tows is approximately 100 km, and it is not uncommon to observe order of magnitude differences in plastic concentration at these scales (Figure 1). Similar variability has been described in other observational studies,^{26,27} and was attributed to local wind-forced currents, eddies and fronts in one numerical ocean model.²⁴ Local wind-driven turbulence has been shown to vertically distribute even buoyant debris to depths unsampled by the surface-towed net,²⁸ introducing variability on short time and space scales. When observed plastic concentrations within the accumulation zone were adjusted for this effect using average wind speed during the tow (SI) and a simple one-dimensional mixing model,²⁸ observed variance increased by 7%. This suggests that more complex two- and three-dimensional processes, such as Langmuir circulation, that are not captured by the simple wind mixing model are required to explain the observed small-scale variability.

The most remarkable example of small-scale variability in the data set was associated with the net tow that measured the highest concentration of plastics (1.232×10^7 pieces km^{-2}). Neighboring tows conducted within a 24-h period, located 32 km and 75 km away, measured concentrations 3 orders of magnitude smaller (2.038×10^4 and 4.791×10^4 pieces km^{-2} , respectively). Wind-driven vertical mixing²⁸ could not account for these differences (adjusted concentrations 3.686×10^4 and 4.913×10^4 pieces km^{-2}). Very light winds (3 kts) occurred during this tow, and shipboard observers described constantly forming and reforming parallel “rivers” of highly visible debris that were

meters in width and extended to the horizon (SI, video). Given the calm conditions, strong density stratification of the local water column and elevated sea surface temperature and salinity measured during the tow (SI, Figure S1), this debris feature might indicate the interaction of buoyant plastic pieces with the convergent flow associated with nonlinear internal waves.^{29,30} While further study would be required to distinguish between this process and other types of submesoscale frontogenesis, this tow provides an example of the potential utility of floating debris patterns in understanding small-scale physical features in the surface ocean. Regardless of the mechanism driving the small-scale spatial variability in plastic concentration, this observation illustrates how the simple orientation of the net tow (along versus across the convergent feature) would give vastly different measured concentration values. Thus, only large data sets employing random sampling can give meaningful generalized results by integrating across such features that are highly variable in space and time.

Temporal Variability and Implications of Sample Distribution. We investigated temporal variability in the defined accumulation zone by computing annual averages over the 11-year period (Figure 3) using data adjusted for the effect of

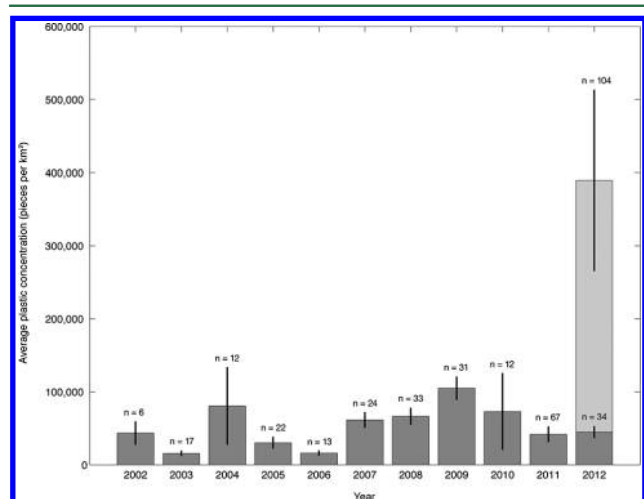


Figure 3. Annually averaged plastic concentrations in the eastern North Pacific accumulation zone (25 to 41°N, 130 to 180°W) from 2002 to 2012, with standard error bars. Data are adjusted for wind-driven vertical mixing. Values above each bar indicate the number of observations in the annual average. The light gray bar indicates the 2012 average including the *Plastics at SEA* expedition, which sampled much closer to the predicted center of accumulation than any other cruise in the record.

wind-driven vertical mixing as described above. We observed large interannual variability with an extremely high value in 2012 that is attributable to data collected on the *Plastics at SEA* cruise, which sampled closest to the predicted center of accumulation. When the 2012 average was computed without *Plastics at SEA* data, the value was comparable to previous years. Considering the spatial variability discussed above and the non-normal distribution of the data, we used the nonparametric Mann–Whitney test to determine whether plastic concentrations measured in the second half of the data set were larger than those in the first half. Plastic concentrations measured from 2007 to 2011 were significantly higher than those from 2002 to 2006 ($U = 3,364$; $P = 0.000004$, one-tailed test) but the statistical significance is dependent on the temporal binning used. Further examination of sample distribution by year also revealed a

potential confounding of observed temporal variability by spatial variability in sampling effort.

To illustrate this point, we examined plastic concentration as a function of distance from the predicted center of accumulation (Figure 4), defined as the location of the maximum concentration in one numerical model²² (31°N, 139°W; star in Figure 6). We found an exponential decrease in observed plastic concentration (nonzero values only) with increasing distance from the model maximum. All measured concentrations greater than 10^6 pieces km^{-2} were located within 1100 km of the predicted center, and all tows measuring zero plastic pieces were located more than 1000 km from this point. When annually averaged plastic concentrations within the accumulation zone were plotted versus average distance from the model maximum, a negative trend was also apparent. This suggests that the closer an annual average sampling location was to the predicted center of accumulation, the higher the resultant annual average plastic concentration. Although the model center is only a prediction of a location that also varies in time, this analysis clearly illustrates that care must be taken in evaluating temporal trends when spatial and temporal variability in the data are confounded by nonrandom variation in sample distribution.

The most recent analysis of surface plastic concentrations in the eastern North Pacific³ reported a two-order of magnitude increase in median concentration between data collected from 1972 to 1985 and 1999 to 2010. In this data set (heretofore referred to as the “Goldstein” data set), the two most recent cruises conducted in 2009 and 2010 were designed to locate and sample regions of the North Pacific subtropical gyre with predicted high plastic concentrations.²⁶ In light of the above discussion, we examined the SEA and Goldstein data sets in order to evaluate the impact of spatial distribution of data on summary statistics (mean and median plastic concentration) that are frequently used to characterize the abundance of plastic debris in the subtropical gyre. We considered four subsets of data within the defined accumulation zone: (1) Historical data in the Goldstein data set collected between 1972 and 1985; (2) Modern data in the Goldstein data set collected in 2009 and 2010 (no samples collected between 1999 and 2008 were located within the accumulation zone); (3) SEA data collected between 2002 and 2012; and (4) A combined modern data set with data collected since 2002 from both studies.

Samples from each subset were spatially averaged in $1^\circ \times 1^\circ$ and $5^\circ \times 5^\circ$ latitude-longitude bins to examine sampling intensity and its effect on estimated plastic concentrations (Figure 5; Table 1). When binned at the 1° scale, the combined modern data set (Figure 5d) containing the largest total number of samples had data in only 28% of bins. This illustrates how even one of the best-sampled regions of the ocean for plastic debris suffers from relatively low spatial coverage. In comparison, the historical data set (Figure 5a) had samples in fewer than 7% of bins, and fewer observations per bin on average. In the historical data set only 62% (37/60) of individual net tows contained plastic, whereas in the modern data sets (Figure 5c, d) between 95% (324/341, SEA) and 100% (116/116, Goldstein) of tows contained plastic.

Because of the large variability in plastic concentration, mean and median values are strongly dependent on the number of observations and their spatial distribution (Table 1). Mean and median values computed from the larger and more broadly distributed SEA data set are 4 to 19 times lower than those computed from the modern Goldstein data set. Simple spatial binning prior to calculation of statistics reduces the bias of heavily

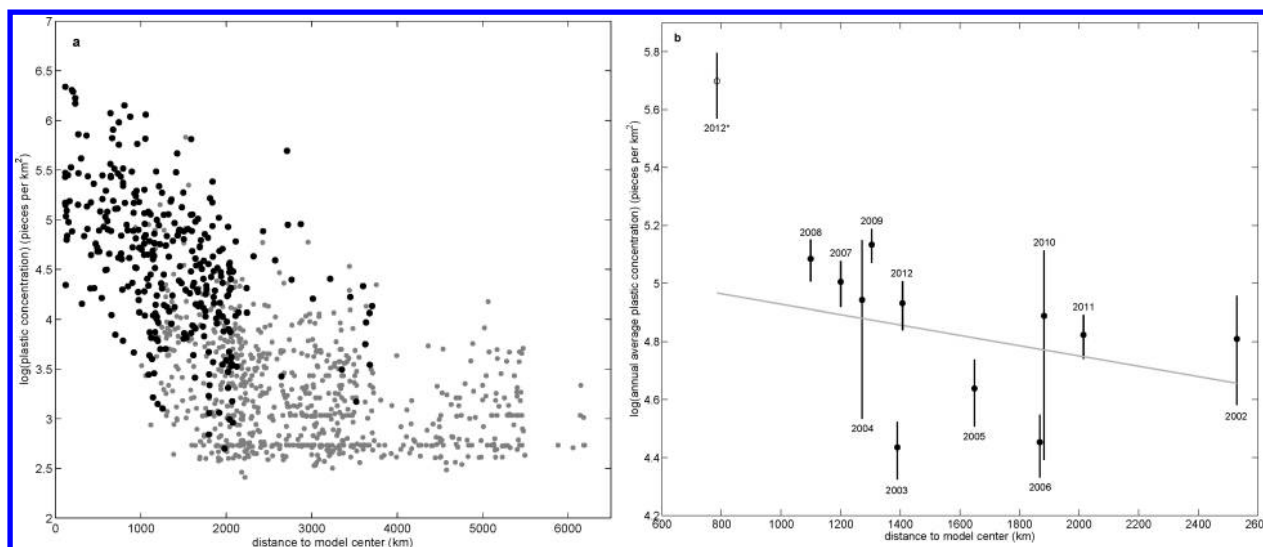


Figure 4. (a) Observed plastic concentration from all tows in SEA data set (nonzero values, not corrected for wind-driven vertical mixing) plotted as a function of distance from the predicted center of accumulation (31°N, 139°W)²². Black dots indicate tows within the defined accumulation zone (25 to 41°N, 130 to 180°W). All tows measuring zero plastic pieces were located more than 1000 km from the predicted center. (b) Annually averaged plastic concentration (with standard error bars) using data corrected for wind-driven vertical mixing in the defined accumulation zone as a function of average distance (of all net tow locations that year) from the model center. Open circle indicates 2012 average including *Plastics at SEA* data (2012*), used in the trend line fit; trend remains if 2012 average without *Plastics at SEA* data (black circle) is used instead. The decrease in plastic concentrations with increasing distance from the predicted center of accumulation in both panels illustrates the difficulty in isolating temporal trends from a data set with large spatial variability and irregular, nonrandom sampling.

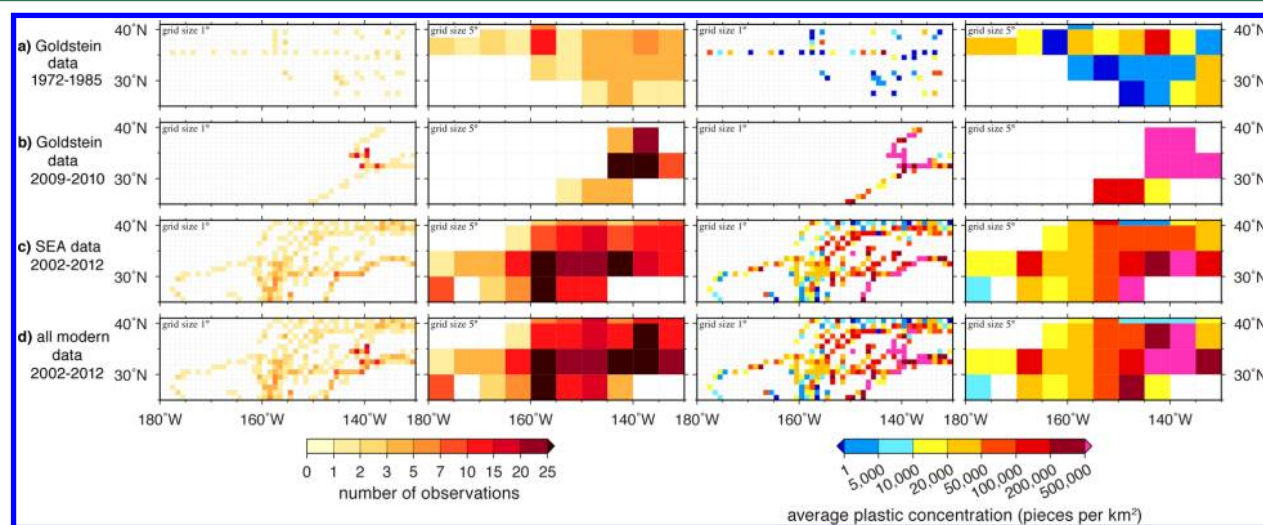


Figure 5. Sampling intensity (number of observations; left two columns) and average plastic concentration (pieces km⁻²; right two columns) in 1° × 1° and 5° × 5° bins within the accumulation zone (25 to 41°N, 130 to 180°W) for the four subsets of data examined: (a) Goldstein data from 1972 to 1985; (b) Goldstein data from 2009 to 2010; (c) SEA data from 2002 to 2012; and (d) all modern data (Goldstein and SEA) from 2002 to 2012. The influence of spatial binning on smoothed maps for each data set is shown in SI, Figure S2.

Table 1. Plastic Concentration (Pieces km⁻²) Summary Statistics Computed within the Accumulation Zone under Different Spatial Binning Schemes^a

	Unbinned		1° × 1° bins		5° × 5° bins	
	mean	median	mean	median	mean	median
Goldstein data 1972–1985 <i>n</i> = 60	17 820	1500	18 160	3500	15 920	10 000
Goldstein data 2009–2010 <i>n</i> = 116	876 900	487 600	557 700	296 000	584 700	666 600
SEA data 2002–2012 <i>n</i> = 341	157 100	33 940	124 600	35 490	124 400	35 050
all modern data 2002–2012 <i>n</i> = 457	339 800	64 000	189 800	39 030	155 900	36 400

^a*Plastics at SEA* expedition data included. Note that each data set sampled different portions and percentages of the accumulation zone, as illustrated in Figure 5. Sources of data in the Goldstein data set listed in SI, Table S1. Mean and median plastic concentration increased by a factor of 10 between 1972 to 1985 and 2002 to 2012 (bold values).

sampled high concentration areas in the modern Goldstein data set. While larger spatial bins can increase statistical confidence, they also reduce spatial resolution (SI, Figure S2). Thus, when interpreting summary statistics it is important to consider sample distribution, including potential sampling biases as well as the number of samples necessary to resolve changes on the scales of interest.²⁶

In this analysis 1° spatial binning reduces the sampling bias in the southeast quadrant of the accumulation zone while still retaining some spatial variation. With this binning, the estimated increase in mean and median plastic concentrations in the North Pacific accumulation zone from 1972–1985 to 2002–2012 using the combined modern data set is approximately a factor of 10, an order of magnitude smaller than the increase reported from the substantially smaller Goldstein data set.³

We expanded the combined modern data set to include all samples collected in the eastern Pacific (17.4°S to 61.0°N; 85.0 to 180.0°W) since 1999, resulting in the most comprehensive modern data set of net-collected plastic debris available. We estimated the mass of floating plastic from these data by integrating plastic concentration over the areas where concentration exceeded 2500 pieces km⁻² (Figure 6) and multiplying by

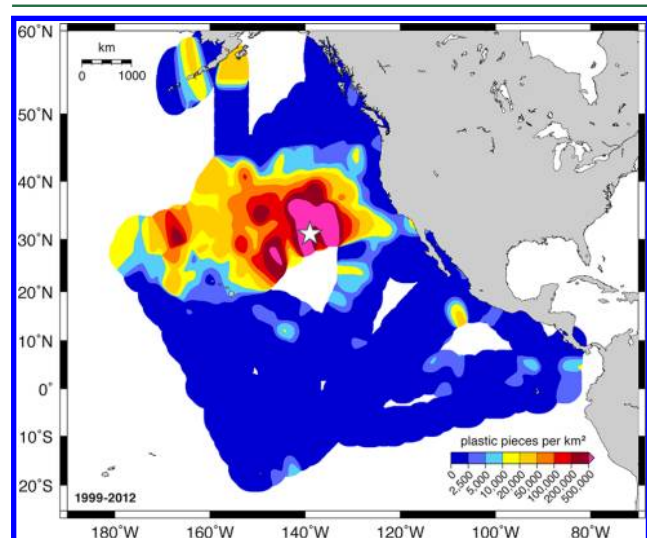


Figure 6. Average plastic concentration (color shading, units of pieces km⁻²) computed as in Figure 2 for all measured surface plastic concentrations described herein from 1999 to 2012 (SEA and Goldstein data sets). The estimated minimum mass of plastic represented in the entire domain (concentration >2500 pieces km⁻²) is 18 280 t. Adjustment for wind-driven vertical mixing for 23% of nonzero tows with available wind data increases this estimate to 21 290 t. White star indicates the location of predicted maximum concentration in a numerical ocean model.²²

average particle mass (1.36×10^{-5} kg),³¹ resulting in 18 280 t. When data adjusted for wind-driven vertical mixing were used (wind data only available for SEA measurements in the accumulation zone (SI)), the estimate increases by 17% to 21 290 t (SI, Figure S3). Both estimates are more than an order of magnitude larger than a similar estimate in the western North Atlantic subtropical gyre (1100 t).⁵ This is because the integrated area is greater in the Pacific than in the North Atlantic (15.5 vs 6.7 million km²) and the average concentration is higher (86 490 vs 8905 pieces km⁻²). However, the area surveyed in the Pacific is also more than four times greater than that surveyed in the

Atlantic, and in neither basin has the full areal extent of the subtropical accumulation zone been determined.

In both the Atlantic and Pacific these integrated mass estimates represent lower bounds on the mass of floating plastic in the areas surveyed. In addition to the potential contribution from unsurveyed areas within the region (white areas in Figure 6), the effect of wind-driven vertical mixing is not fully accounted for because wind data were not available for all tows, and because the one-dimensional mixing model²⁸ does not account for more complex turbulent processes that enhance particle distribution below the sea surface. We also emphasize that measured concentrations do not include small particles that pass through the net mesh, or most large pieces of debris whose mass is much greater than typical net-sampled plastic but that are only rarely captured by the one-meter wide net. Because of scarce observational data, the mass contributions of these size classes have not yet been estimated; thus, it is unknown what fraction of the total mass of floating plastic is represented by our net-based estimate.

Global plastic production increased 41% from 2002 to 2012 (from 204 to 288 Mt)²¹ and reports of municipal solid waste discards in the United States³² indicate a 55% increase from 2001 to 2011 in discarded polyethylene and polypropylene, the most commonly measured floating microplastics.³¹ Although direct plastic input to the ocean via mismanaged waste, wastewater discharge, natural disasters or other mechanisms has not yet been reliably estimated, these trends suggest that the input to the ocean has increased over the time period of our analysis. One might expect that a data set comprising more than 2500 measurements would be able to easily detect such an increase in the amount of plastic floating at the sea surface. Instead, our analysis highlights the challenges in detecting such trends. Although the subtropical gyre region in which plastic debris accumulates is well-described by ocean physics, as demonstrated by multiple oceanographic models and confirmed by our observations of plastic debris, the spatiotemporal variability that determines the small-scale distribution of buoyant debris may be confounded by sample distribution even in very large data sets. This analysis provides an estimate of the minimum mass of floating microplastic debris in the eastern North Pacific (17.4°S to 61.0°N; 85.0 to 180.0°W) based on the most comprehensive net tow data set available to date. Further work must continue to refine this measurement by accounting for sampling variability with more sophisticated statistical techniques, by assessing and quantifying the impacts of physical mechanisms such as turbulent mixing and small-scale fronts on the observed distribution of debris, and by developing large-scale, cost-effective techniques to monitor subtropical gyre accumulation zones that are millions of square kilometers in size.

■ ASSOCIATED CONTENT

● Supporting Information

Detailed description of SEA and Goldstein (Table S1) data sources and processing, and link to the publically available SEA data set. Additional summary statistics on plastic concentrations measured by SEA (Table S2). Digital video and figure illustrating sea surface conditions (Figure S1) during net tow of highest measured plastic concentration. Effect of spatial binning schemes (Figure S2) and adjustment for wind-driven vertical mixing (Figure S3) on mapped plastic concentrations. This material is available free of charge via the Internet at <http://pubs.acs.org/>.

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

We thank the hundreds of SEA Semester students and the scientific staff at Sea Education Association who painstakingly collected and enumerated plastic samples onboard the SSV *Robert C. Seamans*; J. Borrero, L. Lebreton, N. Maximenko, E. van Sebille, and Miriam Goldstein who generously supplied their data; M. Alford, D. Booth, P. Franks, and A. Solow for helpful discussions; and three anonymous reviewers for comments that improved the analysis and manuscript. Figures 1, 2, 5, and 6 were built with open-source Generic Mapping Tools.³³ This work was supported by Sea Education Association, NFWF-NOAA Marine Debris Program (Nos. 2009-0062-002, NA10OAR4320148, Amend. 71), and NSF (Nos. OCE-0087528, OCE-1155379, OCE-1260403, OCE-1352422).

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